Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

Physics Procedia 5 (2010) 145–152

Physics Procedia

www.elsevier.com/locate/procedia

LANE 2010

Welding of glass fibres onto large-scale substrates with high mechanical stability and optical quality

Lorenz Schaefer[a*], Michael Schmidt

[a] Bayerisches Laserzentrum GmbH, Konrad-Zuse-Str. 2-6, 91052 Erlangen, Germany[a]

Abstract

In optical data transmission, adherence is the common method for joining optical components like fibres and lenses. Adhesive joints however have some disadvantages. The transmittable optical power is limited and the boundary layer causes undesired reflections. An alternative method for joining fibers with lenses is welding using CO_2 laser radiation. The irradiation pattern is designed in such a way, that the fibre is welded to the substrate around its whole circumference. Therefore a ring shaped beam is formed by a novel focusing device based on the Schwarzschild objective. The results of the welding experiments show significantly improved characterisitcs of the joint.

Keywords: optics; fibre; laser welding; CO_2 laser; ring focus; return loss

1. Introduction

Optical data transmission is well-established in telecommunications. But its importance is increasing also in systems technology. In order to use the advantages of optical data transmission for communication between rotating and stationary systems, so-called Fibre Optical Rotary Joints (FORJ) are used. These highly precise micro-optical devices enable transmission of high data rates for example between rotating radar antennas or medical sensors and stationary systems for analysis and further processing of the data. Often, the data are transmitted through more than one fibre in order to increase the data transfer rate. To establish an optical connection between the rotating and the stationary fibre bundle, the fibres are fastened to an array of collimator lenses to form a parallel beam which can bridge the freeboard with minimal attenuation. On the opposite side, the beam is focused onto the fibre core again and coupled into it (see Fig. 1). To compensate the rotation, a prism is positioned between the two fibre arrays.

Corresponding author. Tel.: +49-9131-97790-00
E-mail address: l.schaefer@blz.org.

doi:10.1016/j.phpro.2010.08.039

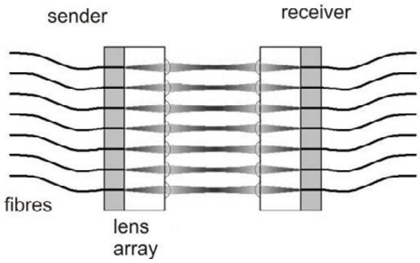

Fig. 1. Coupling between two fibre arrays over freeboard

A great influence on the properties of the coupling device has the joint between the fibre and the collimator lens.

2. Motivation

In the current production process of FORJ's, the fibres are connected to the collimator lenses by adherence. But this method has some disadvantages concerning the optical quality of the joints. The adhesive is chosen in such a way, that the refractive index is nearly the same as the one of the fibre in order to reduce back reflection on the boundary layer. But as there is always a certain difference of the refractive index between the adhesive and the fibre ($\Delta n \approx 0{,}02$), the attenuation of the back reflection does barely exceed -40 dB. For certain applications this value is not sufficient. If a part of the optical power is sent back to the laser source, it has negative effects on its spectral and power stability.

Another reason to examine alternative joining methods for glass fibres is the transmittable optical power. Due to absorption within the adhesive, the transmittable power is up to now limited to 10 mW. If higher power is sent through the joint, the adhesive is being heat up. This leads on the one hand to a change of the refractive index and therefore to higher back reflection. On the other hand, the mechanical stability of the adhesive joint is reduced with higher temperature which can cause a failure of the joint.

The bare fibre has an outer diameter of 125 µm. In order to increase the mechanical stability of the adhesive joint, the fibres are inserted into ferrules with a diameter of 1 mm. The significantly larger area of the ferrule's cross-sectional area allows reaching the needed mechanical stability. But the insertion of the fibre into the ferrule and the following polish process make further process steps necessary. Additionally, the achievable packing density of a fibre array is limited by the relatively high diameter of the ferrule.

These aspects – back reflection, transmittable power, mechanical stability and packaging density –, whose drawbacks are all related to the applied adhesive, demand for research concerning alternative joining methods.

3. Welding process

3.1. Identification of an adequate joining method

Three joining processes are considered to replace the adhesive. Besides welding, these are soldering and bonding. Bonding two components made of fused silica requires pre-processing to create hydrophilic and hydrophobic substrate surfaces. The bonding itself needs both high temperature and high pressure. The temperature during the process has to be 700 … 1000°C at a pressure of 18 MPa [1]. These conditions cannot be set up for joining fibres to a bulk substrate. Therefore bonding is not suitable for this application.

Soldering requires the melting of a lead which incurs a connection with both join partners. The selective melting of the solder could be easily achieved by laser radiation. For joining fibres by soldering it is necessary to apply a glass solder with optical properties compatible to fused silica as the solder will be in the light path and improper refractive indices will cause a higher back reflection. The research for appropriate glass solders showed, that the refractive index is not an important value for typical glass soldering applications (i.e. enclosure) and that therefore they are not documented. The determining of the according values for each glass solder would imply an inappropriate effort. Furthermore, when soldering you have to work with an additional substance in the joining zone, which is not desired.

The third method, welding, is characterized by the absence of any additional material. The melting of the joining partners can be realized by irradiating both of them with a laser beam, preferably a CO_2 laser. The challenge is to form the laser beam in such a way, that both the small fibre and the comparatively large substrate melt simultaneously.

After these considerations, welding is chosen as the joining method which shall replace adhesive joining.

3.2. State of the art

Joining two glass fibres is an established process called splicing. The fibres that shall be joined are brought together at their end faces and aligned precisely. Then an electric arc is activated to fuse the fibre ends and make them connect. Because of the surface tension of the molten glass, the fibres are able to adjust small misalignments by the so-called self centring effect. Although splicing is already well developed, it is not possible to use this method for the application considered here. On the one hand, it is not possible to fuse the bulk material selectively with an electric arc and on the other hand the aspired high packing density of the fibres leaves only very little space for the electrodes at the joining area. These difficulties can be avoided by using a laser beam which can be focused precisely over a long working distance.

Fused silica transmits radiation within a wavelength range of 250 … 3500 nm [3]. Wavelengths above 3500 nm are absorbed and reflected. The most common laser source in this spectral region is the CO_2 laser with a wavelength of 10.6 µm. The Fresnel reflection at this wavelength is about 14 %, so 86 % of the power is absorbed at the surface of the glass.

There have been activities before concerning welding of glass fibres onto glass substrates. In [4] a method is described to weld fibres by laser onto small posts which are located on the substrate surface. By this, the self centring effect known from splicing can be capitalised. The drawback is that the position of the fibre is definite and cannot be adjusted to tolerances of other optical components. In [5] the fibres are welded onto flat substrates by laser irradiation from one side. By this the fibre can be fixed anywhere on the substrate but because of the one-sided irradiation the weld zone is quite small which leads to a low mechanical stability.

With the irradiation pattern described in the following passages it is possible to effectively join the fibre and the substrate with a large cross sectional connection.

3.3. Irradiation pattern

To achieve a stable connection, the fibre shall be irradiated around its whole circumference (see Fig. 2, left). Therefore a ring shaped beam has to be formed. To get such a laser beam out of a Gaussian one there are several possibilities. One is to use an assembly of axicons and a focusing lens. The standard material for transmissive optical components for a wavelength of 10.6 µm is zinc-selenide (ZnSe). This material is very expensive and the required optical components have to be custom made. So the costs for such an optical system are very high. The other way is to use reflective optics. One system to shape a ring is already known: the Schwarzschild objective. This objective consists of two spherical mirrors of which the first one is convex while the second one is concave. The drawbacks of the Schwarzschild objective are the limited focusability and the high shadowing effects that cause a high loss of power.

To capitalize on the advantages of the Schwarzschild objective (ring shaped beam, relatively low costs) and to avoid its disadvantages (shadowing, focusability), the principle design is modified. The first spherical mirror is replaced by a conical mirror with a cone angle of 45°. Thereby, the incoming beam is spread into a plane. The second mirror, that focuses the beam, is described not by a sphere but by a parabolic curve (Fig. 2, right). This leads to a strongly improved focusing quality.

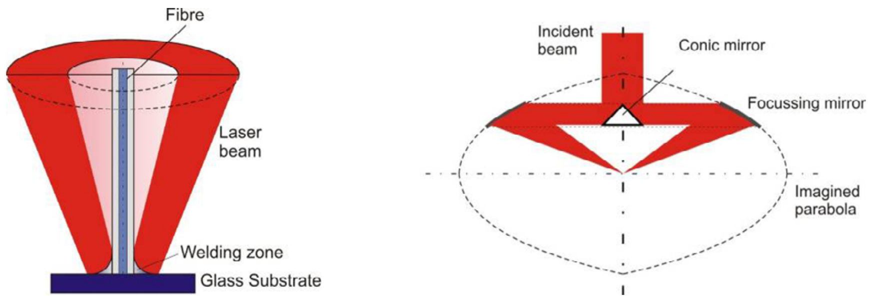

Fig. 2. Irradiation pattern and principle of the focusing device

3.4. System technology

The focusing objective is integrated in a build-up consisting of the laser source, a telescope to widen the beam and to set certain divergence angles and several mirrors to adjust the beam precisely to the objective. Both the fibre and the lens array can be positioned by three linear stages for each joining partner. Thereby an accurate alignment of the fibre both to the corresponding lens and to the focusing objective can be realized. The fibre has to be brought to the joining area from the side and bent by 90° as the focusing device is concentric with the laser beam. The fixation of the fibre to the gripper is achieved by means of low-pressure. To monitor the welding process two cameras are also part of the set-up. While the first one is directed to the joining area, the second camera is arranged below the lens array. This camera is used to observe the shape of the beam that comes through the fibre and is collimated by the lens. The shape and position of the beam gives information about how the position of the fibre changes during the welding process.

4. Welding results

4.1. Experiments

Prior to the welding experiments it is necessary to identify suitable welding parameters. These can be divided into two groups: geometrical and laser parameters. The geometrical parameters affect the shape of the ring and the distribution of the laser power over it. By changing the position of the incident beam relatively to the optical axis of the focusing objective, the distribution of the laser power over the ring can be influenced. The diameter of the focal ring can be influenced by the working distance from the focusing objective. By altering the divergence angle of the laser beam, the broadness of the ring can be changed. The laser parameters are average power and irradiation time.

For the basic experiments an equal distribution of the laser power over the circumference is desired. So the laser beam is aligned concentrically with the focusing objective's optical axis. With the help of experiments, the inner and outer diameter of the ring as well as the laser power is optimized for the development of a good welding seam (see Fig. 3).

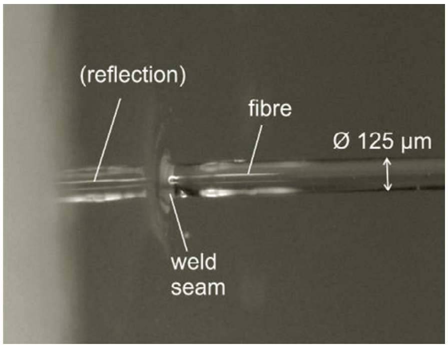

Fig. 3. Welded fibre (t = 15 s, P = 4 W)

The examinations show that the fibre changes its position during the welding process. The reason for this is that the melting of the fibre is always to some degree non-uniform around its circumference. This leads to displacement and bending of the fibre. It is possible to compensate the movement of the fibre by adjusting the position of the lens array during the welding process while monitoring the beam profile from the fibre with the lower camera. This allows getting reproducible and stable weld joints. In the next step the welded fibres are characterized regarding beam profile, tensile strength, back reflection, connection and enclosures.

4.2. Characterization of weld joints

4.2.1. Beam profile

As described above, below the platform holding the lens array, there is a camera for monitoring the profile of the collimated beam. A comparison of the beam profiles before and after the welding process shows that the profile remains principally stable. There is some slight deviance with regard to position and diameter which is caused by movement of the fibre during the process (see Fig. 4).

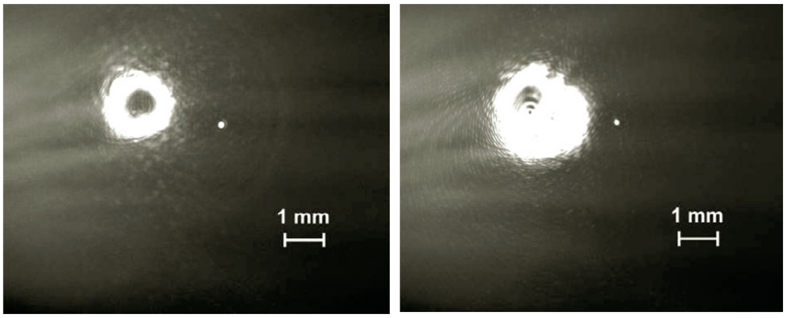

Fig. 4. Profile of collimated beam before (left) and after (right) the welding process

The reason for this movement is slightly irregular irradiation or an angular fibre end face. It is possible to compensate the fibre movement by adjusting the position of the lens array through the linear stages. At the moment, the adjusting is done manually with the help of the camera image. By this method, fibre deviations of 10 µm at best are possible.

4.2.2. Tensile strength

During the assembly process of the rotary joints and for the future application a certain mechanical stability of the joint fibres is required. The adhesive used by default has a tensile strength of 33 MPa [6]. For a fibre with a diameter of 125µm this corresponds with a pull-off force of 0.4 N. For the welded fibres, pulling tests show draw-off strengths of 4.0 N with a deviation of 1.8 N. This corresponds to a tensile strength of 326 MPa, which is 10 times more than the adhesive. The deviation results from the high dependency on shear force which cannot be avoided in every pulling test. But compared with the adhesive, a major improvement of the tensile strength can be observed.

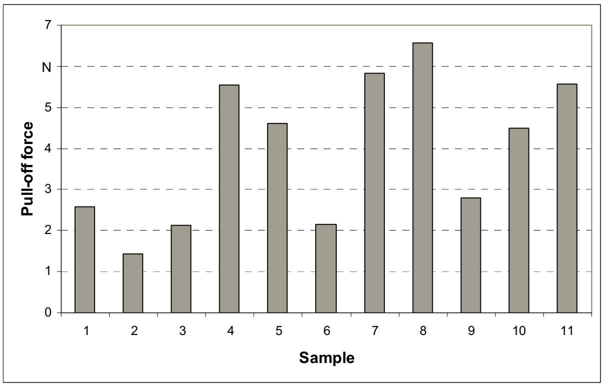

Fig. 5. Measuring of pull-off force

4.2.3. Back reflection

As stated before, an important value for characterizing the quality of an optical data transmission system is the back reflection. The intention is to keep it as low as possible. The back reflection is specified as an attenuation value (return loss). For adhesive joints a return loss of around -40 dB is the best reachable value [7]. With weld joints a much better return loss is possible. The measured mean value is -49.4 dB with a deviation of 0.6 dB, which is in the range of the measurement accuracy. So there is an enhancement of the return loss of nearly 10 dB. This corresponds to an absolute improvement by a factor of 10.

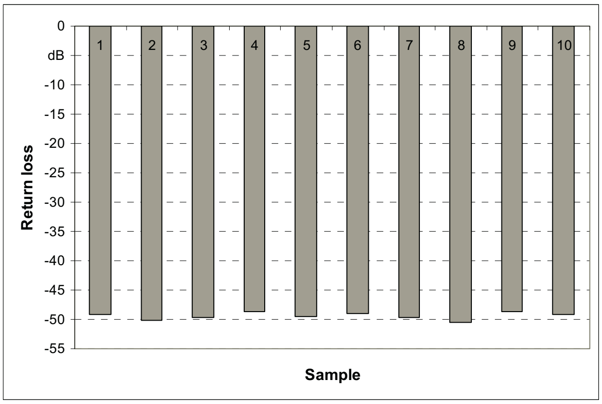

Fig. 6. Measurement of return loss

4.2.4. Connection, enclosures

Another quality feature for the weld joint is the absence of enclosures and the connection to the substrate. To analyse this, cross-sections are made of the welded fibres. The microscopic view of the cross-sections shows that the connection between the fibre and the substrate is nearly perfect. A good concave weld seam is shaped. Also, no enclosures can be found.

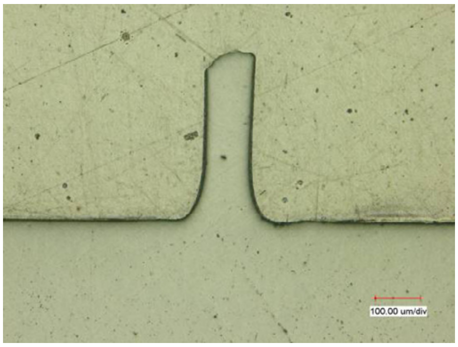

Fig. 7. Cross-section of welded fibre (after prior draw-off test)

4.3. Discussion

Besides the above mentioned advantages of welding compared to adhesives, there are also some drawbacks of the welding method. Due to the necessary systems technology consisting i.e. of a laser source including control and cooling devices and optical components for beam guidance and focussing the costs are higher. Additionally, appropriate measures regarding laser safety must be taken. The packing density of the fibres is limited by the laser-irradiated area of the substrate. The current system is designed to allow a minimum fibre pitch of 1 mm. Contrary to adhesive joints welded fibres cannot be removed from the substrate without destroying the fibre. Therefore, an inaccurately positioned fibre cannot be removed and joint again. This means that a geometrically precise welding of every single fibre is essential for a scrap-free assembly process. This will be assured by further automation and improved control of the fibre position during the welding process.

5. Conclusion

In this article it is presented, how glass fibres can be welded to large glass substrates, i.e. a lens array in order to improve the optical and mechanical properties of the joint. For this a CO_2 laser is applied. The conventional joining method of adherence has several drawbacks with regard to transmittable optical power, return loss or mechanical stability. These can be avoided by laser welding. In order to realise the intended irradiation of the fibre around its circumference a novel focusing device is developed. It is based on the Schwarzschild objective but features improved optical properties. The results that are obtained with this device show significantly improved properties compared to adhesive joints with regard to tensile strength and return loss.

6. Outlook

Although the obtained results are very remarkable, there are some aspects that require further improvement. The main point is the reachable accuracy of the fibre position. To reliably apply the welding process for the production of FORJs, an accuracy of less than 1 µm is necessary. Up to now this is not possible due to the manual positioning of the fibre. An approach for this objective is to integrate a position sensor for the fibre in combination with a closed-loop control to drive the linear stages. It has to be determined, if the positioning of the fibre during the welding process is feasible with the required sub-µm precision. A way to improve the positioning is to shorten the length of the fibre which looms over the gripper and prevents a direct movement of the fibre end. With these measures a far better reproducibility and accuracy of the fibre position is possible.

References

1. S Jean-Pierre Colinge: Silicon-on-Insulator Technology. Materials to VLSI. 3 Auflage. Springer Netherlands, 2004
2. A. R. Mirza, A. A. Ayon: Silicon wafer bonding: Key to MEMS high-volume manufacturing. In: Sensors. 15, Nr. 12, 1998, S. 24.–33
3. http://www.sciner.com/Opticsland/FS.htm, from 03/10.
4. Patent WO 02/50589 A1 “Projector lens”
5. Patent DE 102 04 012 B4 “Verfahren zum stoffschlüssigen Verbinden mikrotechnischer Bauteile”
6. Datasheet DELO-PHOTOBOND® GB310
7. Information from Schleifring GmbH
8. Göbel, M./Hildebrand, J.: Schweißen von Quarzglas, VDM Verlag, Saarbrücken 2008.
9. Schaefer, L., Popp, G.: Final report for BFS Research Cooperation ForPhoton, 2010